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## Two-dimensional electron solid formation in Si inversion layers

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(Received 26 March 1991)

We have studied experimentally the nature of the giant resistance peaks previously observed in two-dimensional (2D) low-density electron layers on a Si surface at low temperatures and magnetic fields. The measurements of the low-frequency impedance of the metal-oxide-semiconductor structure indicate that this effect takes place homogeneously over the "2D bulk" and measurements of the Hall resistance show that the development of the giant resistance peaks is not related to a diminution in the concentration of delocalized electrons. Both diagonal and Hall conductivities were found to reach their *minima* near half-integer filling of Landau levels, where the single-particle density of states should be at its *maximum* value. These results evidently contradict the single-particle localization picture. At the same time, the experimental results are well consistent with the formation of an electron solid. This solid forms at low electron densities  $n_s \lesssim 10^{11} \text{ cm}^{-2}$  and temperatures  $T \lesssim 1 \text{ K}$  in weak or possibly even zero magnetic fields and drives both  $\sigma_{xx}$  and  $\sigma_{xy}$  to zero with decreasing temperature. In the vicinity of integer filling factors 1 and 2, the solid melts, thus providing well-defined quantized-Hall-resistance states.

### I. INTRODUCTION

At sufficiently low temperatures, a low-density two-dimensional (2D) electron gas is expected to undergo a transition to a solid phase. So far, the two-dimensional electron solid (ES) phase has been observed in an electron system at the surface of liquid helium<sup>1,2</sup> and in GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures.<sup>2-8</sup> The ES phase on a helium surface is formed at zero magnetic field in the classical regime:  $E_F \ll kT$ ,  $E_{ee}$  [where  $E_F = \hbar^2 \pi n_s / m^*$  is the Fermi energy;  $E_{ee} = e^2 (\pi n_s)^{1/2} / \epsilon$ , the energy of the electron-electron interaction;  $n_s$ , the electron concentration;  $m^*$  and  $e$ , respectively, the effective mass and the elementary charge;  $T$ , the temperature; and  $\epsilon$ , the dielectric constant]. In heterostructures the electron solidification has been experimentally observed only at high magnetic fields in the extreme quantum limit:  $\nu < \nu_c \approx 0.2$  (here  $\nu \equiv n_s / n_H$  is the filling factor and  $n_H$  is the Landau-level degeneracy number). This  $\nu_c$  value is in agreement with theoretical results,<sup>9</sup> according to which the energy of Wigner crystal becomes lower than that of the electron liquid state at  $\nu < 0.15$ .

The essential difference between heterostructures and Si metal-oxide-semiconductor field-effect transistors (MOSFET's) is the presence of relatively strong disorder in the latter. Even in the extremely-high-mobility Si MOSFET's, where the importance of the electron-electron interactions was proved,<sup>10</sup> the disorder impedes the formation of the incompressible quantum liquid and turns the Si inversion layer into an insulator state at  $\nu < 0.5$  at any  $n_s$ . Thus the above cited results<sup>9</sup> could hardly be related to this system. At the same time, it

was pointed out<sup>11</sup> that having a larger number of defects reduces the mean-square displacement of electrons from their equilibrium lattice sites (due to breaking of infinitesimal translational invariance) and thus aids in the formation of the ES. Besides, the higher energy of electron-electron interactions (due to lower mean  $\epsilon$  at Si/SiO<sub>2</sub> interface) and lower kinetic energy of electrons for the same  $n_s$  (due to higher  $m^*$ ) both favor the formation of the ES in Si inversion layers, increasing the "cold melting" electron concentration  $n_c$ .<sup>12</sup> Nevertheless, no reliable evidence for the existence of the ES in Si MOSFET's has been reported so far.<sup>13</sup>

Recently, an unexpected behavior of the longitudinal magnetoresistance,  $R_{xx}$ , has been observed<sup>14</sup> in extremely high-mobility Si inversion layers at temperatures  $T < 1 \text{ K}$ . Lowering the carrier concentration below  $\approx 10^{11} \text{ cm}^{-2}$  results in an increase of the characteristic  $R_{xx}$  peaks at filling factors around  $\nu \sim 1.5$  and 2.5 by more than 5 orders of magnitude. The temperature dependence of  $R_{xx}$  maxima at low  $n_s$  was found to be  $R_{xx} \propto e^{\Delta/kT}$ , with  $\Delta$  of order 1 K. The peaks remained separated by the ordinary integer quantum Hall effect (IQHE) minima near  $\nu = 1$  and 2, where  $R_{xx}$  diminished at lowering temperature. The observed  $R_{xx}$  anomalies were attributed to single-particle magnetic-field-induced localization modulated by the IQHE, or to the formation of an electron solid.

Based on the experimental results,<sup>14</sup> one could not give preference to either of these models. The questions to be solved were the following: (i) Is the observed phenomenon a "2D bulk" effect, or is the sharp increase in resistance a consequence of the narrowing of the effective

sample width due to the magnetic freeze-out? (ii) Is the effect related to a diminution in the concentration of delocalized electrons, which might be due to single-particle localization? Some experimental data<sup>14</sup> seem to support the 2D bulk nature of the effect, but the importance of these questions demands a more reliable experimental basis for this statement.

Here we report experimental results, which clearly show that the development of the giant  $R_{xx}$  maxima is not related either to a diminution in the concentration of delocalized electrons or to a decrease in the effective sample width. Neither can a simple increase of the disorder as  $n_s$  decreases explain simultaneously both the giant peaks of  $R_{xx}$  and the existence of the well-defined IQHE minima as the latter requires well-separated Landau levels and hence small disorder. It was also proved that the measured sample resistance is not affected by the contact resistances.

At the same time, the observed anomalies in resistance are well consistent with the formation of an electron solid, which melts at filling factors around 1 and 2 thus providing quantized-Hall-resistance states. Both the diagonal and Hall conductivities of this solid were found to tend to zero at low  $T$  and  $n_s$ , while  $\sigma_{xy}$  becomes  $\ll \sigma_{xx}$ . Though the present theoretical models do not describe dc transport properties of the ES in details, the main experimental results, such as vanishing diagonal and Hall conductivities and melting of the solid at integer filling factors, agree with available theoretical predictions.

## II. EXPERIMENT

The experiments were performed with high-mobility Si MOSFET ( $\mu^{\text{peak}} \approx 4.5 \times 10^4 \text{ cm}^2/\text{Vs}$  at  $n_s \approx 3 \times 10^{11} \text{ cm}^{-2}$  and at  $T = 0.25 \text{ K}$ ) of the “Hall-bar” geometry ( $0.8 \times 5 \text{ mm}^2$ ). The oxide thickness was about 2000 Å, and the high- $n_s$  zero-field capacitance was 690 pF. Similar results were obtained for high-mobility samples from various wafers.

### A. ac-resistance measurements

At low  $n_s$  and in the mK temperature region, the high- $R_{xx}$  phase has been observed<sup>14</sup> to spread over the entire range of magnetic fields, making  $\rho_{xy}$  measurements practically impossible. Nevertheless, when the electron solidification is only emerging (until  $R_{xx}$  is less than  $\approx 300 \text{ k}\Omega$ ), the  $\rho_{xy}$  measurements may give valuable information on the concentration of “delocalized” (i.e., current carrying) electrons,  $n_d$ . Hall resistance (in contrast to Hall conductance) is actually known to be almost independent of scattering processes even at  $\omega_c \tau < 1$ :<sup>15</sup>  $\rho_{xy} = H/(n_d e c)$  (here  $\omega_c$  is the cyclotron frequency and  $\tau$  is the electron lifetime). Measurements of longitudinal and Hall resistances were performed at 6.7 Hz with very low alternating current ( $< 1 \text{ nA rms}$ ) in a linear regime, by the four-terminal technique using two lock-in amplifiers with 100-M $\Omega$  input resistance.

Figure 1 shows  $R_{xx}$  and  $\rho_{xy}$  dependencies on the inverse filling factor (proportional to the magnetic field) for four different electron concentrations determined by

the gate voltage [the  $n_s(V_g)$  dependence was extrapolated from the high- $n_s$  region]. At high  $n_s$  [Fig. 1(d)], well-developed IQHE plateaus in  $\rho_{xy}$  are clearly seen, as are the respective  $R_{xx}$  minima.  $R_{xx}$  peaks at  $\nu \sim 1.5$  and 2.5 are equal to 14 and 2.5 k $\Omega$ , respectively, and only slightly depend on  $n_s$  over the range of electron concentrations  $n_s \geq 1.1 \times 10^{11} \text{ cm}^{-2}$  (see Fig. 2). Lowering the carrier concentration below this value causes the  $R_{xx}$  peaks to grow by several orders of magnitude (while the lower- $H$  peak becomes much greater than the higher- $H$  one) but they remain separated by the minima around  $\nu = 1$  and 2. The Hall resistance at half-integer filling factors remains almost unchanged and equal approximately to  $H/(n_s e c)$  [Fig. 1, (c) to (a)]. The  $R_{xx}$  minima and the Hall plateaus at  $\nu = 3, 4$ , and 5 disappear, and the  $R_{xx}$  peaks at  $\nu = 2.5, 3.5, 4.5$ , and 5.5 join the single peak at  $\nu \sim 2.7$ .  $R_{xx}$  and  $\rho_{xy}$  for  $n_s = 0.86 \times 10^{11} \text{ cm}^{-2}$  are not

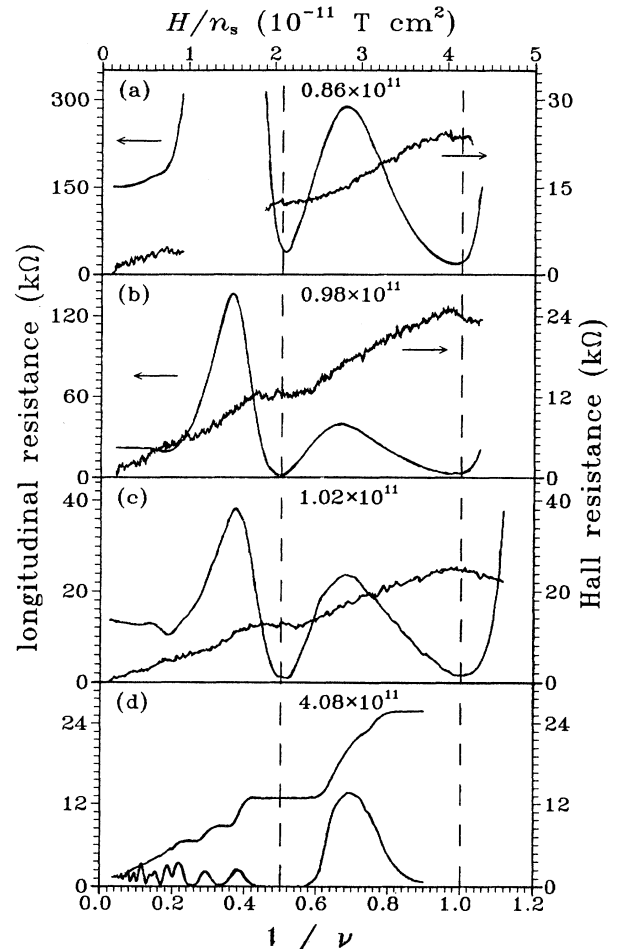


FIG. 1. Longitudinal and Hall resistances for different electron concentrations as functions of  $\nu^{-1} \propto H$  obtained by four-terminal measurements. The numbers at the tops of the graphs show  $n_s$  in units of  $\text{cm}^{-2}$ . The data were taken at  $T = 240 \text{ mK}$  and 6.7 Hz with the ac source-drain current 0.7 nA rms, (a)–(c), and 2 nA (d). The distance between potential contacts used was 2.5 mm, and the sample width was 0.8 mm.

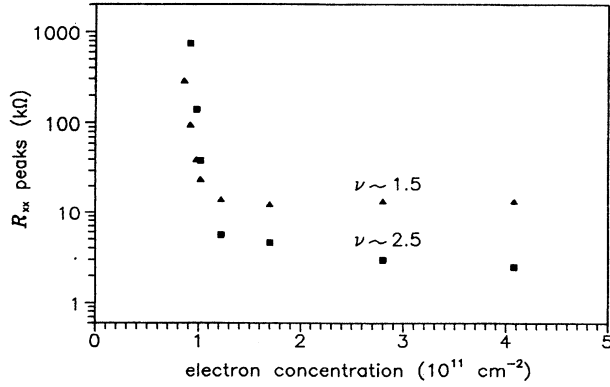


FIG. 2.  $R_{xx}$  peaks as functions of the electron concentration for two fixed filling factors (the triangles correspond to the higher- $H$  peak at  $\nu \sim 1.5$ , and the squares correspond to the lower- $H$  peak at  $\nu \sim 2.7$ ).  $T = 240$  mK.

represented in the interval  $0.25 < \nu^{-1} < 0.45$  because the phase of the measured ac voltage changed noticeably when  $R_{xx}$  exceeded 300 kΩ, and this prevented us from measuring the resistances at  $n_s$  below  $0.86 \times 10^{11} \text{ cm}^{-2}$  using the ac technique. Upon increasing the current, electron transport becomes strongly nonlinear (this and its attendant phenomena will be reported elsewhere).

Since the value of the Hall resistance does not change noticeably, one may assert that the concentration of electrons carrying an electrical current is still nearly equal to  $n_s$  even when  $R_{xx}$  is as high as 300 kΩ (i.e.,  $R_{xx}$  is more than 2 orders of magnitude greater than its measured maximum value for  $\nu \sim 2.5$  in the high- $n_s$  region and than the predicted<sup>16</sup> upper limit for the magnetoresistance of a 2D electron gas). However, this does not yet prove that the effect is not related to single-particle localization. In principle, the magnetic freeze-out could lead to narrowing of the effective sample width due to the appearance of insulating “islands” related to inhomogeneities of the background potential. In this case, the measured  $R_{xx}(H)$  dependence would be much higher than that for high  $n_s$ , while  $\rho_{xy}(H)$ , determined by  $n_d$  inside conducting regions away from the insulating “islands,” would remain the same. In order to find out whether this “partial localization” takes place, we studied the impedance of the system “channel gate.”

### B. Impedance measurements

The impedance  $\mathcal{Z}$  was measured in the frequency range 3–67 Hz using an  $RC$  bridge. Two orthogonal components of the bridge imbalance signal were measured simultaneously using a lock-in amplifier with 100-MΩ input resistance.

The real part of the bridge imbalance signal,  $\text{Re}(\mathcal{Z})$ , is inversely proportional to the diagonal conductivity  $\sigma_{xx}$  (Refs. 17 and 18) with a prefactor of order 1.  $\text{Re}(\mathcal{Z})$  dependencies on the inverse filling factor for different  $n_s$  are represented in Fig. 3(a). The sharp peaks at integer filling factors on the two lowest curves (relatively

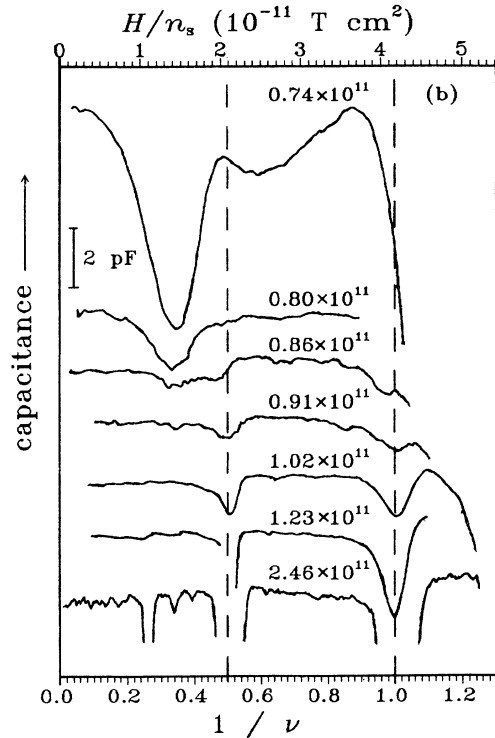
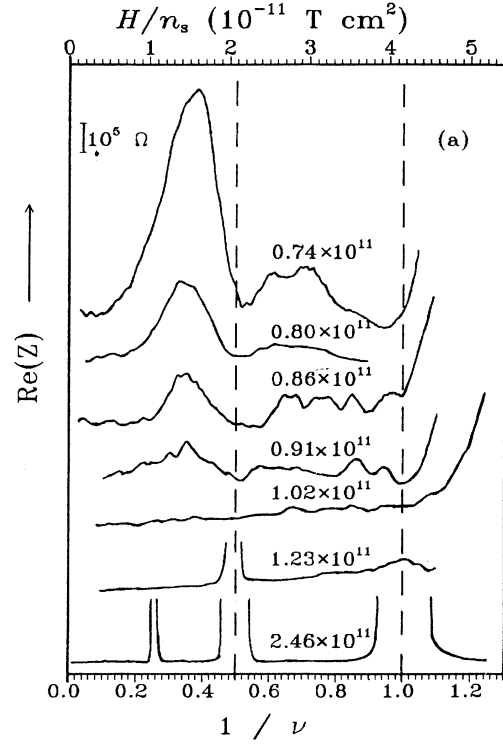


FIG. 3. (a) Real part of the impedance of the MOS structure and (b) the capacitance channel gate vs inverse filling factor taken at  $T = 240$  mK and at 6.7 Hz. The numbers under the curves correspond to  $n_s$  in units of  $\text{cm}^{-2}$ . The curves are shifted vertically for clarity.

high  $n_s$ ) reflect the minima of  $\sigma_{xx}$ , which occur when the Fermi energy lies between neighboring sublevels. As  $n_s$  decreases, the magnitudes of these peaks reduce, presumably due to an increase in disorder, and new  $\sigma_{xx}^{-1}$  peaks begin to appear near  $\nu \sim 1.5$  and  $2.7$  reflecting the development of diagonal conductivity *minima* at these filling factors. This is evidently inconsistent with the single-particle picture in which  $\sigma_{xx}$  reaches its *maxima* at half-integer filling factors where the single-particle density of states is at a maximum value. Note that the dependencies of  $\text{Re}(\mathcal{Z}) \propto \sigma_{xx}^{-1}$  on  $1/\nu$  at low  $n_s$  are similar to those for  $R_{xx}$ , and the maxima of  $\sigma_{xx}^{-1}$  for  $n_s \approx 0.86$  to  $0.74 \times 10^{11} \text{ cm}^{-2}$  are of order  $10^5$ – $10^6 \Omega$  (i.e., of the same order as the  $\rho_{xx}$  values obtained by four-terminal measurements). This consistency of  $\rho_{xx} = \sigma_{xx}^{-1}/(1 + \sigma_{xy}^2/\sigma_{xx}^2)$  and  $\sigma_{xx}^{-1}$  indicates that  $\sigma_{xy} \ll \sigma_{xx}$  at this  $n_s$  region.

To determine whether the conductivity is homogeneous over the sample area on the scale exceeding the oxide thickness (2000 Å), we measured the imaginary part of the impedance,  $\text{Im}(\mathcal{Z})$ , which is approximately equal to  $\Delta C/(\omega C^2)$  [here  $\Delta C \equiv C - C_r$ , where  $C$  is the capacitance of the metal-oxide-semiconductor (MOS) structure,  $C_r$  is the reference capacitance of the bridge, and  $\omega$  is the frequency]. As long as measured capacitance is frequency independent, all changes in  $C$  can be attributed to changes in the thermodynamic density of states.<sup>17</sup> The measured capacitance must diminish<sup>19</sup> with increasing frequency when  $(\omega C)^{-1}$  becomes lower than the mean  $\sigma_{xx}^{-1}$  value due to the “skin effect”,<sup>18</sup> thus the frequency dependence of  $C$  allows one to estimate the average inverse conductivity. If the electrons were localized over most of the sample area (as in the “partial localization” model), the measured capacitance, being proportional to the conductive area of the sample, would be much lower than its high- $n_s$ , zero- $H$  value.

Capacitance dependencies on  $1/\nu$  [Fig. 3(b)] at  $n_s > 0.9 \times 10^{11} \text{ cm}^{-2}$  show the expected minima at *integer* filling factors corresponding to minima of the density of states ( $C$  is almost frequency independent in this  $n_s$  region). The magnitudes of these minima diminish as  $n_s$  decreases because of the increase in the density of states between neighboring levels. This is related to the level broadening and decreasing level separation which occurs as  $n_s$  is decreased and the minima shift to lower  $H$  values. At  $n_s < 0.8 \times 10^{11} \text{ cm}^{-2}$ , new clearly distinguishable minima emerge at *intermediate* filling factors. The changes in capacitance measured at 6.7 Hz did not exceed 1%, which confirms that practically all of the sample area takes part in charging and discharging, and hence the area of the insulating “islands” (if any) is negligibly small. The highest- $H$  maximum of the capacitance for  $n_s = 0.74 \times 10^{11} \text{ cm}^{-2}$ , which corresponds to the  $\sigma_{xx}^{-1}$  minimum at  $\nu \approx 1$ , is displaced to the low- $H$  region, presumably due to the development of the magnetic freeze-out at  $\nu < 1$  and the corresponding diminution of the effective sample area. The magnitude of these new capacitance peaks was found to vary linearly with frequency in a range 3–67 Hz, and therefore we attribute these peaks to a diminution in the dissipative conductivity of 2D electrons but not to a diminution in the density of states. The corresponding average  $\sigma_{xx}^{-1}$  for  $\nu \sim 2.7$  at

$n_s \approx 0.74 \times 10^{11} \text{ cm}^{-2}$  is of the order of  $10^6 \Omega$  and agrees with the results obtained from  $\text{Re}(\mathcal{Z})$  and  $R_{xx}$ . This consistency also confirms the homogeneity of the effect over the “2D bulk.”

One might suppose that the spatial scales of the conductive channels and the insulating islands would be much less than the oxide thickness. In that case, the measured capacitance would be approximately equal to its high- $n_s$ , zero- $H$  value even if the area of the insulator greatly exceeded the conductive area. However, the electron density within the conductive channels would then be much higher than its mean value  $n_s$ , in contradiction with the Hall resistance measurements.

The  $H$  dependencies of  $\text{Re}(\mathcal{Z})$  and of the capacitance at low  $n_s$ , both of which are determined by  $\sigma_{xx}$ , are similar to each other (apart from a change in sign) though the capacitance is *not* sensitive to the resistance of contacts [unless  $R_{\text{cont}} \ll (\omega C)^{-1}$ ] whereas  $\text{Re}(\mathcal{Z})$  is. Moreover, the impedance measurements were performed with various sets of contacts, and the results were found to be qualitatively the same. This proves that the observed resistance anomalies are not affected by the resistance of the contacts.

### C. Conductivities

The results of the impedance measurements evidently contradict the “partial localization” model, and hence the current distribution is nearly homogeneous. Thus one may recalculate the magnetoconductivities  $\sigma_{xx}$  and  $\sigma_{xy}$  from the data for  $R_{xx}$  and  $\rho_{xy}$  using the total sample width. The calculated magnetoconductivity phase diagrams,  $\sigma_{xx}$  ( $\sigma_{xy}$ ), are illustrated in Fig. 4, allowing one to trace the transformation of the ordinary high- $n_s$  maxima at half-integer filling factors into the new state. For high  $n_s$ , the  $\sigma_{xx}$  ( $\sigma_{xy}$ ) dependence [Fig. 4(d)] has its ordinary form,<sup>20</sup> with  $\sigma_{xx}$  maxima between  $0.2e^2/h$  and  $0.3e^2/h$  achieved at half-integer fillings. The phase diagram does not significantly change qualitatively or quantitatively (in accordance with Ref. 20) in the “metallic range” of concentration (i.e., down to  $n_s \approx 1.1 \times 10^{11} \text{ cm}^{-2}$ ). Below this value, the points corresponding to filling factors  $\nu \sim 1.5$  and  $2.5$  begin to move to the point  $\sigma_{xy} = \sigma_{xx} = 0$ , following the trajectories shown by the arrows in Figs. 4(c) to 4(a), while the points corresponding to the integer filling factors ( $\nu = 1$  and  $2$ ) remain fixed. It must be noted that  $\sigma_{xy}$  becomes much less than  $\sigma_{xx}$  on approaching the point (0,0), as was expected from the consistency of  $\rho_{xx}$  and  $\sigma_{xx}^{-1}$  (see above). Changing the magnetic field induces the transitions between the states with  $\sigma_{xx} \rightarrow 0$  and  $\sigma_{xy}/\sigma_{xx} \rightarrow 0$  and the IQHE states with  $\sigma_{xx} \rightarrow 0$  and  $\sigma_{xy} \rightarrow e^2/h$  or  $2e^2/h$ . At concentrations below  $0.9 \times 10^{11} \text{ cm}^{-2}$ , the points corresponding to the integer filling factors also begin to move to the point (0,0), reflecting the destruction of the IQHE minima. Nevertheless, both the diagonal and Hall conductivities always remain much higher than those for  $\nu \sim 1.5$  and  $2.7$ .

### III. DISCUSSION

The above reported experimental results are evidently in contradiction with the single-particle localization pic-

ture. Considering an alternative interpretation of the effect—the formation of a pinned electron solid due to strong interaction between electrons—we note that in zero or low magnetic field the electron-electron interaction energy  $E_{ee} = e^2(\pi n_s)^{1/2}/\epsilon \sim 100$  K at  $n_s = 10^{11}$  cm $^{-2}$  is the most important parameter, greatly exceeding the Fermi energy  $E_F = \hbar^2 \pi n_s / 2m^* \sim 7$  K. In quantizing magnetic fields, when the splittings between energy levels become higher than  $E_{ee}$ , the electron-electron interaction energy depends not on the total electron concentration but rather on the concentration of quasielectrons or quasiholes at the Landau levels: $^9 n_q \equiv |n_s - \mathcal{N} n_H|$ , where  $\mathcal{N}$  is the integer nearest to  $\nu$ . Therefore, in quantizing magnetic fields  $E_{ee} \sim e^2(\pi n_q)^{1/2}/\epsilon$  reaches its maxima ( $\sim 70$  K at  $H = 2$  T) at half-integer filling factors and approaches zero as  $n_q \rightarrow 0$  (i.e., at integer values of  $\nu$ ). Thus it is natural to attribute the observed phenomena to the formation of the 2D electron solid and its subsequent melting in the vicinity of the integer filling factors.

Two main theoretical models for the electron solid have been studied intensively: the Wigner solid (WS) and the charge-density wave (CDW). In the case of the

ideal WS in a zero- $H$ , zero- $T$  limit, the cold melting is expected to occur $^{2,12}$  at  $n_s > n_c = (r_c^2 \pi a_B^2)^{-1}$ , where  $a_B = \hbar^2 \epsilon / (m^* e^2)$  is the Bohr radius, and the estimates of the critical  $r_c$  value vary over a wide range from 4.5 (Ref. 21) to 33. $^{22,23}$  The higher effective mass and the lower dielectric constant both increase the “cold melting” concentration  $n_c$  in Si inversion layers by a factor of  $\sim 20$  in comparison to the value for GaAs/Al $_x$ Ga $_{1-x}$ As heterostructures. The presence of a magnetic field was predicted $^{11}$  to increase  $n_c$  further so that for  $H = 2$  T the melting concentration was estimated $^{11}$  to be about  $10^{11}$  cm $^{-2}$ , which corresponds to our experimental data. As discussed above, in a quantizing magnetic field the WS should melt at integer filling factors when the splitting between neighboring levels becomes greater than  $E_{ee}$ . The estimated valley and spin splittings for  $\nu = 1$  and 2 under the conditions of our experiment are of the order of a few K, $^{12,19}$  which is much less than the calculated  $E_{ee}$ . However, we must take into account that (i) the experimental estimation $^{10}$  of  $E_{ee}$ , taken for the same sample, showed that  $E_{ee}$  in quantizing magnetic fields in Si inversion layers is about 1 order of magnitude less than its expected theoretical value, and (ii) the splitting between neighboring energy levels is strongly enhanced (in comparison to its initial value) due to exchange effects $^{12,19}$  when the Fermi energy lies between these levels. Thus the range of existence for the state under study is in reasonable consistency with the theoretical predictions for a WS. However, we cannot say at present whether the observed electron solid is a pinned crystal or an electron glass with no long-range order.

The critical temperature  $T_c$  for the CDW formed at the lowest Landau level was calculated in the Hartree-Fock approximation $^{24}$  to be

$$T_c \sim 0.56 \nu (1 - \nu) \frac{e^2}{l_H \epsilon}$$

(where  $l_H$  is the magnetic length). Its maximum value estimated for  $H = 2$  T is about 15 K (achieved at  $\nu = \frac{1}{2}$ ) and far exceeds the corresponding experimental value, which is approximately 1 K. However, the experimental results for  $E_{ee}$  cited above $^{10}$  allow one to suppose the value of  $T_c$  in Si inversion layers also be 10 times lower than predicted by theory, which makes it quite reasonable. The quasiparticles form the solid state at filling factors  $\nu_m < \nu < 1 - \nu_m$  around the half-integer  $\nu$ , and remain in the gaseous state away from this region (i.e., around the integer  $\nu$ ), where

$$\nu_m = \frac{1}{2} - \left( \frac{1}{4} - \frac{kT \epsilon l_H}{0.56 e^2} \right)^{1/2},$$

which follows from the condition that  $T < T_c$ . The results for  $T_c$  are also expected to be valid for higher energy levels because only the fractional part of  $\nu$  is of importance (see above). Hence the theoretical predictions for a CDW in a magnetic field do not contradict our experimental results either.

In the presence of impurities, both  $\sigma_{xx}$  and  $\sigma_{xy}$  for the electron solid were predicted $^{25}$  to vanish as  $T \rightarrow 0$ . This

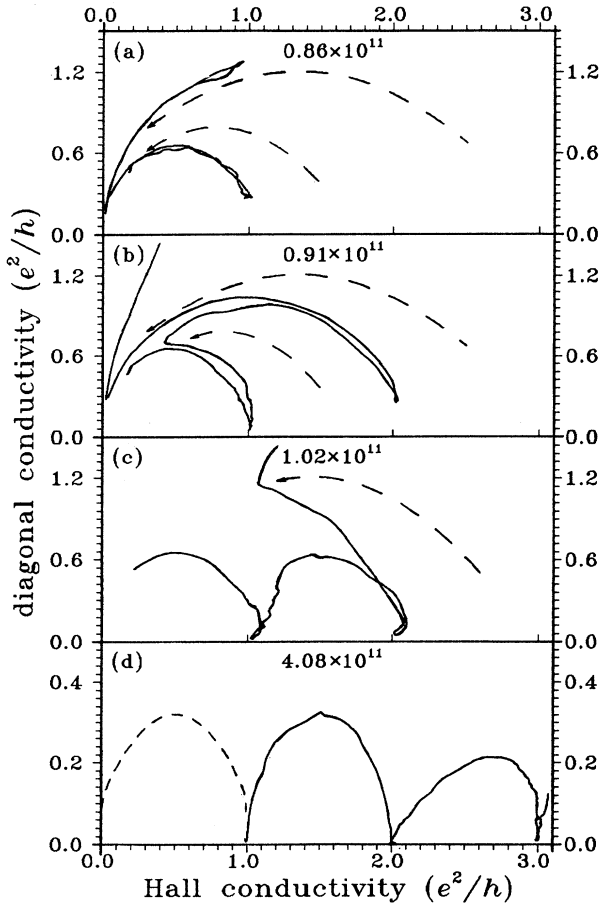


FIG. 4. Magnetoconductivity phase diagrams at different electron concentrations for  $T = 240$  mK. The numbers at the tops of the figures show  $n_s$  in units of cm $^{-2}$ . The dot-dashed curve in the lowest figure shows schematically the expected (Ref. 20) high- $n_s$   $\sigma_{xx}$  ( $\sigma_{xy}$ ) dependence for  $0 < \nu < 1$ .

is in accordance with our experimental results. Considering the data obtained for the Hall resistance, we arrive at the following conclusions.

(i) *All* electrons (including those in Landau levels below the Fermi energy) participate in formation of the electron solid (presumably because  $E_{ee}$  exceeds the *unenhanced* splittings between neighboring levels, and the levels below the Fermi energy are mixed). Indeed, if only the electrons occupying the highest Landau level were condensed, then those from the lower  $N - 1$  levels would give the usual "gaseous" contribution,  $(N - 1)e^2/h$ , to the Hall conductivity, and this would contradict our experimental data for  $\sigma_{xy}$  (Fig. 4).

(ii) The electron solid can move in an applied electric field at  $n_s$  not far below  $n_c$  [Figs. 1(a)–(c)] since *all* electrons have been found to carry a current. If the electron solid were rigidly pinned, an electron transport could only arise due to a thermal excitation over a gap between ground and excited states, and in this case  $R_{xy}$  would be much higher than its experimentally determined value.

In closing this paper, we would like to compare the transport properties of the electron solid in Si inversion layers with those in GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures. First, the solid phase in heterostructures was found to exist at filling factors slightly above 0.2 and also below 0.2 (Refs. 2–8) in the limit of high magnetic field and

on the background of the incompressible electron liquid. In Si inversion layers, however, the solid phase exists in between integer filling factors and appears at essentially low fields. Second, the longitudinal resistance in the presence of the solid phase in both cases diverges drastically as  $T \rightarrow 0$ .<sup>4–6</sup> The measurements of the Hall resistance in heterostructures<sup>4</sup> also showed that the concentration of the delocalized electrons did not change significantly for the anomalous  $R_{xx}$  peak at  $\nu$  slightly above 0.2. Strong nonlinearity is characteristic of transport measurements in heterostructures in the presence of the electron solid<sup>6</sup> and this is also in the case in Si. The similarity of the transport properties in both systems can be considered as additional evidence for the formation of the solid phase in Si inversion layers.

## ACKNOWLEDGMENTS

We are grateful to Professor H. van Kempen for his interest in this work, and to Jos Rook, Tos Berendschot, and Van Lung for their technical assistance. One of us (S.V.K.) is also thankful to Dr. S. G. Semenchinsky for useful discussions, and V.M.P. would like to acknowledge the University of Nijmegen for its hospitality and financial support.

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<sup>1</sup>C. C. Grimes and G. Adams, Phys. Rev. Lett. **42**, 795 (1979).

<sup>2</sup>D. C. Glatthi, G. Deville, V. Duburcq, F. I. B. Williams, E. Paris, B. Etienne, and E. Y. Andrei, Surf. Sci. **229**, 344 (1990).

<sup>3</sup>E. Y. Andrei, G. Deville, D. C. Glatthi, F. I. B. Williams, E. Paris, and B. Etienne, Phys. Rev. Lett. **60**, 2765 (1988).

<sup>4</sup>R. L. Willett, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **38**, 7881 (1988).

<sup>5</sup>H. W. Jiang, R. L. Willett, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **65**, 633 (1990).

<sup>6</sup>V. J. Goldman, M. Santos, M. Shayegan, and J. E. Cunningham, Phys. Rev. Lett. **65**, 2189 (1990).

<sup>7</sup>H. Buhman, W. Joss, K. von Klitzing, I. V. Kukushkin, A. S. Plaut, G. Martinez, K. Ploog, and V. B. Timofeev, Phys. Rev. Lett. **66**, 926 (1991).

<sup>8</sup>R. G. Clark, R. A. Ford, S. R. Haynes, J. F. Ryan, A. J. Turberfield, P. A. Wright, C. T. Foxon, and J. J. Harris, in *High Magnetic Fields in Semiconductors Physics III*, edited by G. Landwehr (Springer-Verlag, Berlin, in press).

<sup>9</sup>P. K. Lam and S. M. Girvin, Phys. Rev. B **30**, 473 (1984).

<sup>10</sup>S. V. Kravchenko, D. A. Rinberg, S. G. Semenchinsky, and V. M. Pudalov, Phys. Rev. B **42**, 3741 (1990).

<sup>11</sup>A. G. Eguiluz, A. A. Maradudin, and R. J. Elliott, Phys. Rev. B **27**, 4933 (1983).

<sup>12</sup>T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

<sup>13</sup>The results of D. C. Tsui [Solid State Commun. **21**, 675

(1977)], S. Kawaji and J. Wakabayashi [*ibid.* **22**, 87 (1977)], T. A. Kennedy, R. J. Wagner, B. D. McCombe, and D. C. Tsui [*ibid.* **22**, 459 (1977)], and B. A. Wilson, S. J. Allen, and D. C. Tsui [Phys. Rev. B **24**, 5887 (1981)] suggest the transition to electron solid state in Si MOSFET's. However, these results were not explained by further investigations and remain inconclusive.

<sup>14</sup>M. D'Iorio, V. M. Pudalov, and S. G. Semenchinsky, Phys. Lett. A **150**, 422 (1990); in *High Magnetic Fields in Semiconductors Physics III*, edited by G. Landwehr, Springer Series in Solid State Sciences (Springer-Verlag, Berlin, in press).

<sup>15</sup>*The Quantum Hall Effect*, edited by R. E. Prange and S. M. Girvin (Springer-Verlag, New York, 1987).

<sup>16</sup>S. I. Dorozhkin, S. Koch, K. von Klitzing, and G. Dorda, Pis'ma Zh. Eksp. Teor. Fiz. **52**, 1233 (1990) [JETP Lett. **52**, 652 (1990)].

<sup>17</sup>A. M. Voshchenkov and J. N. Zemel, Phys. Rev. B **9**, 4410 (1974).

<sup>18</sup>V. T. Dolgoplov and S. I. Dorozhkin, Poverkhnost **2**, 5 (1985) (in Russian); see also Ref. 19.

<sup>19</sup>I. V. Kukushkin, S. V. Meshkov, and V. B. Timofeev, Usp. Fiz. Nauk **155**, 219 (1988) [Sov. Phys. Usp. **31**, 511 (1988)].

<sup>20</sup>A. M. M. Pruisken, Phys. Rev. B **32**, 2636 (1985).

<sup>21</sup>P. M. Platzman and H. Fukuyama, Phys. Rev. B **10**, 3150 (1974).

<sup>22</sup>D. Ceperley, Phys. Rev. B **18**, 3126 (1978).

<sup>23</sup>M. Imada and M. Takahashi, J. Phys. Soc. Jpn. **53**, 3770 (1984).

<sup>24</sup>H. Fukuyama, P. M. Platzman, and P. W. Anderson, Phys. Rev. B **19**, 5211 (1979).

<sup>25</sup>H. Fukuyama and P. A. Lee, Phys. Rev. B **18**, 6245 (1978).